THERMAL CONSTRAINTS ON HIGH-PRESSURE GRANULITE METAMORPHISM OF SUPRACRUSTAL ROCKS L.D. Ashwal, P. Morgan, and W.W. Leslie*, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, TX 77058. *also at Dept. Earth & Space Sci., UCLA, Los Angeles, CA 90024.

We examine here the circumstances leading to the formation and exposure at the Earth's surface of supracrustal granulites. These are defined as sediments, volcanics, and other rock units which originally formed at the surface of the Earth, were metamorphosed to high-pressure granulite facies (T = 700-900^{o}C, P = 5-10 kbar), and reexposed at the Earth's surface, in many cases underlain by "normal" thicknesses of continental crust (30-40 km). Examples are numerous, and are represented by Archean through Tertiary occurrences (Table 1). Three stages in the formation of such rocks must be accounted for: transport from the surface to depths of 15-30 km, heating to 700^{o}C or more, and reexposure at the surface.

Tectonic underthrusting is the most plausible mechanism to transport surface rocks to 15-30 km depths. This can be achieved either by continental underthrusting and consequent double-thickening to 60-80 km (4, 26), or by underthrusting of thin plates, with only minor increase in crustal thickness (18). Each of these cases places distinctly different constraints on possible thermal histories for the supracrustal rocks, as discussed below. Although burial of supracrustal rocks to 15-30 km by continuous sedimentary-volcanic loading is a possibility, it must be a remote one, based on isostatic considerations.

There are several mechanisms by which such rocks can be re-exposed at the surface. Uplift is a natural consequence of isostatic readjustment in thickened continental crust, and where double-thickening has occurred by underthrusting, the top of the underthrust plate can be reexposed by subsequent erosion. The granulite exposures in the Massif Central have been suggested to have formed in this way (1). Large-scale isostatic movements, however, cannot account for uplift to the surface of thin slivers underthrust below continental crust of normal (35-40 km) thickness. In this case, tectonic mechanisms such as deep reverse faults would be necessary to account for surface exposures of supracrustal granulites. This usually results in a crustal cross-section, with a continuous increase in metamorphic grade from greenschist to granulite toward the fault (8). Examples of granulite terranes thought to have developed in this way include the Ivrea Zone of the Alps (16), and the Kapuskasing Structural Zone of Ontario (19). Thus, although particular tectonic conditions may be required for the burial and subsequent reexposure of supracrustal rocks of granulite grade, these conditions are easily explained in the framework of plate tectonics.

The heating step is perhaps the most difficult to account for. Intrusion of magmas at temperatures greater than 1000^{o}C could provide the necessary heat for granulite metamorphism, but most granulite terranes do not contain the requisite volumes of mafic intrusives to explain the heating directly by mantle-derived magmas (25). Hot crustal melts such as tonalites could provide a solution for terranes containing such materials, such as for the Tertiary granulites of the Coast Ranges of British Columbia (10, 11). The tonalitic melts may be produced by anatexis or hybridization (29), but the ultimate heat

Table 1. Compilation of Some Supracrustal Granulite Occurences

LOCATION	ROCK UNITS	P-T CONDITIONS*	AGE (OF META.)	REF.
ARCHEAN				
Beartooth Mtns., Montana	Basalts, Pelites, Ironstones	7 kbar 650-750°C	3400 Ma	9
Enderby Land, Antarctica	Pelites, Ironstones, Calc-Silicates, Marbles	8-10 kbar 900-950°C	3000 Ma	24
Malene, West Greenland	Marbles, Calc-Silicates Metavolcanics	7-9 kbar 650-850°C	3000 Ma	6
Lewisian, Scotland	Pelites, Aluminous & Siliceous Sediments	10-13 kbar 800-860°C	2700-2900 Ma	15,28
Sierra Leone	Pelites, Iron Formations	6-9 kbar 720-820°C	2800 Ma	21
Pikwitonei Domain, Manitoba	Pelites, Iron Formations	10-11 kbar 900-1000°C	2400-2800 Ma	27
Kapuskasing Structural Zone, Ont.	Metabasalts, Marly Sediments	6-8 kbar 700-800°C	2600-2700 Ma	19
PROTEROZOIC				
Broken Hill, Australia	Pelites, Calc-Silicates	5-6 kbar 650-800°C	1700 Ma	20
Adirondacks, New York	Marbles, Quartzites Semi-Pelites	6-8 kbar 650-750°C	1000-1100 Ma	5
PHANEROZOIC				
Ivrea Zone, No. Italy	Pelites, Marbles, Migmatites	8-11 kbar 700-820°C	450 Ma	12,22
Massif Central, France	Pelites, Metabasalts	11 kbar 800°C	350-400 Ma	1,2
Coast Ranges, British Columbia	Metabasalts, Calcic & Aluminous Sediments	5-8 kbar 750-850°C	62 Ma	10,11

* In some cases P-T estimates were determined from rock units adjacent to or in association with the supracrustal granulites.

source for such melts is probably mantle-derived magmatism.

Other heating mechanisms are somewhat constrained by the way in which the supracrustals are reexposed after metamorphism. Consider first exposure by erosion and isostatic readjustment of crust double-thickened by underthrusting. Several models of this type have been published which attempt to predict the thermal histories of various points within the crust during erosion following an "instantaneous" underthrusting event (3, 7, 25). Most of these models assume that the supracrustal rocks near the thrust are heated primarily during the thermal relaxation of the perturbed temperature profile (commonly a "sawtooth" profile) following underthrusting. The effects of erosion are to increase the temperature at any particular depth, but to decrease the maximum temperature acquired by any particular rock unit during thermal relaxation as it rises to the surface. Maximum possible temperatures will be attained by any particular rock unit if thermal relaxation is complete before erosion occurs. Although we recognize that this condition is geologically unrealistic, we use it to demonstrate that granulite metamorphism of supracrustal rocks in the middle of double-thickened crust by conductive heating alone is highly improbable.

A range of possible steady-state geotherms in double-thickened crust are shown in Fig. 1. Most of the possible geotherms either fail to attain sufficient temperatures at mid-crustal levels to cause granulite metamorphism of the underthrust supracrustal rocks and/or exceed the probable solidus temperature near the base of the crust, suggesting that melts would form, and that the assumption of a conductive geotherm and conductive thermal relaxation is invalid. Only geotherms generated assuming extreme upper crustal enrichment of heat production with little or no mantle heat flow (e.g. E and F, Fig. 1) can produce mid-crustal granulites without lower crustal melting, and these conditions must be regarded as highly improbable. Thus, we condlude that conductive heating alone cannot produce granulites from supracrustal rocks in the middle of a double-thickened crust. This mechanism could, however, be supplemented by magmatic heating as discussed above, and could apply to granulite terranes containing substantial volumes of crustally derived granitic melts produced during the metamorphism (21).

A possible mecahnism to account for granulite terranes which lack evidence for magmatic activity during metamorphism invloves underthrusting of thin ($<$ 5-10 km) slivers of supracrustals. Conductive heating alone could produce granulite metamorphism of these supracrustal rocks without necessarily melting the lowermost crust. These rocks must then be exposed by a subsequent tectonic overthrusting event, as they cannot be brought to the surface isostatically during erosion.

Conductive heating in a double-thickened crust to produce granulite metamorphism at mid-crustal levels can be augmented or dominated by two mechanisms: (i) preheating of the crust prior to underthrusting, and (ii) shear heating along the thrust. Preheating of the overthrust crust is likely to occur by arc magmatism if significant subduction preceeds overthrusting. Preheating may also occur associated with pre-orogenic granites (4), which may be associated with delamination of the mantle portion of the lithosphere prior to overthrusting. Thus if the lower portions of the overthrust plate are sufficiently hot (800^{o}-1000^{o}C), thermal relaxation could produce

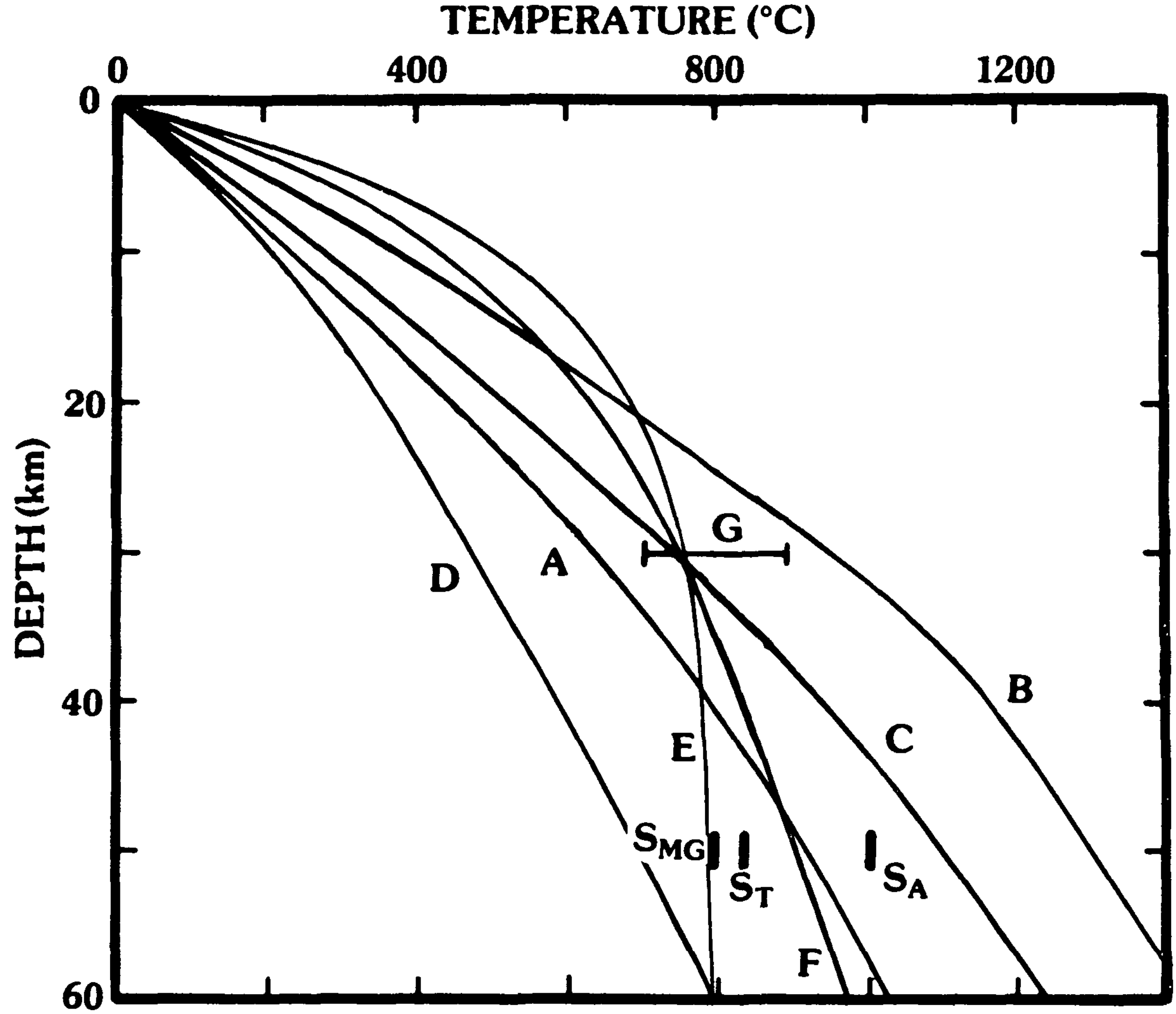

Fig. 1. Possible equilibrium geotherms in double-thickened crust composed of two 30 km thick plates to illustrate the relatioship between mid-crustal and Moho temperatures. Heat producing elements, where present, are assumed to be exponentially distributed with depth through the plates, with a depth distribution parameter of 10 km (e.g. 13). Curves A, B, and C were calculated assuming identical heat production in both upper and lower plates. In curve A, a heat production, A_s, of 2.0 $\mu W\ m^{-3}$ was assumed at the top of each plate with a mantle heat flow, Q_m, of 27 $mW\ m^{-2}$ (typical shield value); for curve B, A_s = 4.0 $\mu W\ m^{-3}$, Q_m = 27 $mW\ m^{-2}$; and for curve C, A_s = 2.0 $\mu W\ m^{-3}$, Q_m = 36 $mW\ m^{-2}$. Curves C, D, and E were calculated assuming all heat production to be concentrated in the upper plate. For curve D, A_s = 4.0 $\mu W\ m^{-3}$, Q_m = 27 $mW\ m^{-2}$; for curve E, A_s = 20 $\mu W\ m^{-3}$, Q_m = 0; for curve F, A_s = 14.4 $\mu W\ m^{-3}$, Q_m = 17 $mW\ m^{-2}$. A uniform crustal thermal conductivity of 2.5 $W\ m^{-1}\ K^{-1}$ was assumed. The granulite temperature field at mid-crustal levels (30 km) is marked by G. S_{MG}, S_T, and S_A are solidus temperatures at 50 km depth for muscovite granite, tonalite, and amphibolite, respectively, assuming H_2O present sufficient for formation of muscovite, biotite, and hornblende, but without excess H_2O (from ref. 29). If thinner plates are considered, the geotherms can be scaled linearly to yield similar mid-crustal/Moho temperature relationships. It is not proposed that very high temperatures are likely in the lower plate - the curves are used to illustrate the point that in a purely conductive regime, granulite metamorphism temperatures are highly unlikely to be generated at mid-crustal levels without significant melting in the lower plate.

supracrustal granulites in the top of the underthrust plate without initiating melting below. Alternatively, or in addition, shear heating on the thrust may also occur. It is usually assumed that this shear heating is of minor importance (e.g. 5), but if high frictional stresses can be maintained on the thrust, shear heating can produce melting (17). Thus, temperatures sufficient for granulite metamorphism may be generated in the region of the thrust plane. The efficiency of shear heating is still a subject of much uncertainty (e.g. 14, 23), but should this mechanism produce sufficient temperatures for granulite metamorphism, the metamorphic isograds would be strongly controlled by faults.

In summary, we propose 5 possible heating mechanisms to account for granulite metamorphism of supracrustal rocks:

1. Magmatic heating, (a) from mantle-derived melts, or (b) from anatectic products of mantle-derived melts.
2. Thermal relaxation of perturbed temperature profiles following underthrusting and double-thickening of continental crust. This necessarily results in crustal melting of the lower plate unless crustal heat generation and mantle heat flow are very low. Granulite terranes formed in this way may be indistinguishable from those produced by mechanism 1(b).
3. Thermal relaxation after underthrusting of thin slivers of supracrustal rocks below continental crust of "normal" thickness (30-40 km). This avoids anatexis during metamorphism, but requires a subsequent tectonic event to elevate the granulites to the surface.
4. Major preheating of the upper plate (for example by arc magmatism or pre-orogenic granites) prior to underthrusting.
5. Shear heating caused by high frictional stresses along the thrust plane.

It is clear that granulite metamorphism of supracrustal rocks is not the simple consequence of continental collision. Magmatism and/or subsequent tectonic events almost certainly play a fundamental role in the heating and reexposure of the metamorphosed supracrustal rocks. Identification of the thermal histories of such terranes requires detailed input from field studies and geochronology. In particular, the relationship of spatially associated granitic rocks to the metamorphic event(s) must be carefully evaluated.

REFERENCES

1. Albarede, F. (1976) Thermal models of post-tectonic decompression as exemplified by the Haut-Allier granulites (Massif Central, France). Bull. Soc. geol. France 7, 1023-1032.
2. Bernard-Griffiths, J., Cantagrel, J-M, and Duthou, J-L (1977) Radiometric evidence for an Acadian tectonometamorphic event in western Massif-Central, Francais. Contrib. Mineral. Petrol. 61, 199-212.
3. Bickle, M.J., Hawkesworth, C.J., England, P.C., and Athey, D.R. (1975) A preliminary thermal model for regional metamorphism in the Eastern Alps. Earth Planet. Sci. Lett. 26, 13-28.
4. Bird, P. (1978) Initiation of intracontinental subduction in the Himalaya. J. Geophys. Res. 83, 4975-4987.
5. Bohlen, S.R., Essene, E.J., and Hoffman, K. (1980) Update on feldspar and oxide thermometry in the Adirondack Mountains, New York. Bull. Geol. Soc. Amer. 91, 110-113.
6. Dymek, R.F. (1983) Supracrustal rocks, polymetamorphism, and evolution of the southwest Greenland Archean gneiss complex. In, Holland, H.D. and Trendall, A.F. (Eds.), Patterns of Change in Earth Evolution. Dahlem Konferenzen, Springer-Verlag, in press.
7. England, P.C. and Richardson, S.W. (1977) The influence of erosion upon the mineral facies of rocks from different metamorphic environments. J. geol. Soc. Lond. 134, 201-213.
8. Fountain, D.M. and Salisbury, M.H. (1981) Exposed cross-sections through the continental crust: implications for crustal structure, petrology, and evolution. Earth Planet. Sci. Lett. 56, 263-277.
9. Henry, D.H., Mueller, P.A., and Wooden, J.L. (1981) Early Archean granulite facies supracrustal assemblages, eastern Beartooth Mountains, Montana (abstr.) G.S.A. Abstr. with Prog. 13, 471.
10. Hollister, L.S. (1975) Granulite facies metamorphism in the Coast Range Crystalline belt. Can. J. Earth Sci. 12, 1953-1955.
11. Hollister, L.S. (1982) Metamorphic evidence for rapid (2 mm/yr) uplift of a portion of the central gneiss complex, Coast Mountains, B.C. Can. Mineral. 20, 319-322.
12. Koppel, V. (1974) Isotopic U-Pb ages of monazites and zircons from the crust-mantle transition and adjacent units of the Ivrea and Ceneri Zones (southern Alps, Italy). Contr. Mineral. Petrol. 43, 55-70.
13. Lachenbruch, A.H. (1968) Preliminary geothermal model of the Sierra Nevada. J. Geophys. Res. 73, 6877-6989.
14. Lachenbruch, A.H. and Sass, J.H. (1980) Heat flow and energetics of the San Andreas fault zone. J. Geophys. Res. 85, 6185-6222.
15. Okeke, P.O., Borley, G.D., and Watson, J. (1983) A geochemical study of Lewisian metasedimentary granulites and gneisses in the Scourie-Laxford area of north-west Scotland. Mineral. Mag. 46, 1-9.
16. Mehnert, K.R. (1975) The Ivrea Zone, a model of the deep crust. N. Jb. Miner. Abh. 125, 156-199.
17. Molnar, P., Chen, W.-P., and Padovani, E. (1983) Calculated temperatures in overthrust terrains and possible combinations of heat sources responsible for the Tertiary granites in the Greater Himalaya Jour. Geophys. Res. 88, 6415-6429.
18. Oxburgh, E.R. (1972) Flake tectonics and continental collision. Nature 239, 202-204.
19. Percival, J.A. and Card, K.D. (1983) Archean crust as revealed in the Kapuskasing uplift, Superior Province, Canada. Geology 11, 323-326.
20. Phillips, G.N. and Wall, V.J. (1981) Evaluation of prograde regional metamorphic conditions: their implications for the heat source and water

activity during metamorphism in the Willyama Complex, Broken Hill, Australia. Bull. Mineral. 104, 801-810.

21. Rollinson, H.R. (1982) P-T conditions in coeval greenstone belts and granulites from the Archean of Sierra Leone. Earth Planet. Sci. Lett. 59, 177-191.
22. Schmid, R. and Wood, B.J. (1976) Phase relationships in granulitic metapelites from the Ivrea-Verbano Zone (northern Italy). Contrib. Mineral. Petrol. 54, 255-279.
23. Scholtz, C.H., Beaven, J., and Hank, T.C. (1979) Frictional metamorphism, argon depletion, and tectonic stress on the Alpine fault, New Zealand. J. Geohpys. Res. 84, 6770-6782.
24. Sheraton, J.W., Offe, L.A., Tingey, R.J., and Ellis, D.J. (1980) Enderby Land, Antarctica- an unusual Precambrian high-grade metamorphic terrain. J. geol. Soc. Austr. 27, 1-18.
25. Thompson, A.B. (1981) The pressure-temperature (P-T) plane viewed by geophysicists and petrologists. Terra Cognita 1, 11-20.
26. Toksoz, M.N. and Bird, P. (1977) Modelling of temperatures in continental collision zones. Tectonophysics 41, 181-193.
27. Weber, W. and Scoates, R.F.J. (1978) Archean and Proterozoic metamorphism in the northwestern Superior Province and along the Churchill-Superior boundary, Manitoba. In, Metamorphism in the Canadian Shield, Geol. Surv. Canada., Paper 78-10, 5-16.
28. Wood, B.J. (1975) The influence of pressure, temperature and bulk composition on the appearance of garnet in orthogneisses - an example from South Harris, Scotland. Earth Planet. Sci. Lett. 26, 299-311.
29. Wyllie, P.J. (1977) Crustal anatexis: an experimental review. Tectonophysics 43, 41-71.